DEVELOPMENT OF STABILISED BRICK AND MORTAR USING BIOMASS WASTE

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ABSTRACT

This paper reports the potential of using Cereal Ash (CA) and Bottom Ash (BA) waste generated from biomass combustion plants for the manufacture of stabilised bricks and sustainable masonry mortar for brick joints and plaster. For the stabilised brick production, the CA waste and BA waste were used as full substitutes for primary clay and on the other hand, Magnesium oxide Ash (MA) was used as a partial substitute for conventional stabilisers. The blending for the production of the masonry mortar was accomplished by the partial replacement of Portland Cement (PC), Quicklime (L1) or Hydraulic lime (L2) with large volumes (up to 70%) of CA waste. The properties investigated under this study include material characterisation and compressive strength and durability using freeze-thaw tests. The results obtained suggest that there is potential for the manufacture of sustainable construction materials such as bricks and mortar from CA, BA and MA waste streams.

Keywords: Sustainability, Cereal Ash waste, mortar, Bottom Ash waste, Magnesium oxide Ash, stabilisation.

1.0 INTRODUCTION

The main advantages of using biomass waste such Cereal (CA) Ash and Bottom Ash (BA) wastes in this current study are their abundance as waste materials, consistency and homogeneity. With the exception of rice husk ash which has widely been specifically investigated, most other cereal ashes (such as from corn and/or wheat as in the current work) have unexplored potential for use for low cost and environmentally friendly building development. Converting specific waste streams such as CA and BA wastes to a usable resource could be viewed as resource preservation and environmental enhancement from a visual impact and amenity point of view. Furthermore, the embodied energy in recovering and reusing such waste for use in making non-fired bricks and blocks is less than the embodied energy in quarrying clay.

Work on the possible utilisation of all waste streams arising from the biomass sector, quarrying and construction activities has been on-going. For example, there are numerous studies on the use of fly ash and lime mixtures for making stabilised bricks (Anderson and Jackson, 1983, Kumar, 2003). In addition to lime, other solidifying agents such as Ground Granulated Blastfurnace Slag (GGBS), calcined gypsum and dextrin are added in the production. Chindaprasirt and Pimraksa (2008) reported on the microstructures and mineralogical compositions of stabilised fly ash granule bricks. Turner (1997) conducted a research on fly ash-clay soil mixtures. The studies indicate that increasing fly ash content had a considerable effect

47 on the strength properties of the soil, and the strength strongly depended on the water-binder
48 ratio.

49

50 The use of rice husk ash waste with cement and lime, to improve the engineering properties of
51 the soil was conducted by Ali et al (1992) and Muntohar (2009). The results by the researchers
52 showed that the presence of rice husk ash significantly increased both the compressive and
53 tensile strength values of the stabilised clay soil. Among the various applications for bottom ash
54 and cereal ash waste, a number of studies are available on the use of bottom ash in road
55 construction (Alkemade et al., 1994), for compressed bricks (Freidin 2007, Shon et al., 2009) or
56 as an aggregate in concrete (Pera et al., 1997). Extensive research has been carried out by the
57 current research team (Oti et al., 2010) on the utilization of between 20-80% of GGBS as
58 Portland cement replacement for masonry mortar production.

59

60 In all the reported studies on the possible utilisation of waste for building bricks and mortar
61 production, there are only a few reported cases for the conversion of wastes to sustainable
62 construction material using non-rice-related Cereal Ash (CA) waste and Bottom Ash (BA)
63 wastes (Alkemade et al., 1994, Pera et al., 1997, Freidin 2007, Shon et al., 2009, Ezcurra et al.,
64 2001, Ortiz De Zárate et al., 2005, Allegrini et al., 2014) for the manufacture of stabilised
65 masonry bricks and mortar under the same project. Thus, the main objective of this paper is to
66 report on the strength properties of cylinder and cube test specimens made with the various
67 formulations using the CA and BA waste types and the laboratory-scale production of full-size
68 building bricks. The paper also includes preliminary work on the possible utilisation of

Magnesium oxide Ash waste (MA) for making mortar that would be suitable for cementing the bricks made with CA and BA in this study. This part of the investigation was prompted by the close proximity of the MA waste in the same region of Spain (Pamplona, in Navarre region) where the CA and BA were located. The paper is relevant to those involved in the use of waste and industrial by-products for the development of low carbon building materials, including civil and construction engineers, and engineers involved in waste and resource management. This paper could be also of interest to people working in developing countries, where the use of waste and industrial by-products for energy-efficient construction practices is much more widespread and much more significant.

2.0 MATERIALS

The materials used consisted of Cereal Ash (CA) and Bottom Ash (BA) wastes, Magnesium oxide Ash (MA), an industrial by-product material from the mining of magnesite by a company based in Spain (Magnesitas Ltd.), Ground Granulated Blastfurnace Slag (GGBS), Portland Cement (PC), Lime and sand.

2.1 Cereal (CA) Ash and Bottom Ash (BA) wastes

The cereal Ash (CA) and Bottom Ash (BA) wastes used for this study was generated by a biomass power plant burning waste from the growing of cereals. Table 1 shows some physical, elemental and chemical composition of these wastes, as provided by the supplier - Acciona Energy Ltd, Navarra, Spain. No further re-characterisation of these materials was carried out by the authors.

92 **2.2 Magnesium Oxide Ash (MA).**

93 The magnesium oxide Ash (MA), an industrial by-product used for this study is a quarry ash
94 from burned magnesia stone. The MA waste was supplied by Magnesitas Ltd., Navarra, Spain.
95 Table 2 shows the data on oxide composition and sieve analysis of MA waste as supplied by
96 Magnesitas Ltd.

97

98 **2.3 Ground Granulated Blastfurnace Slag (GGBS)**

99 Ground Granulated Blastfurnace Slag (GGBS) in compliance with BS EN 15167-1, 2006,
100 supplied by Civil and Marine Ltd, Llanwern, Newport, UK, was used throughout the research
101 study. Some physical properties, oxide and some chemical composition of GGBS are presented
102 in Table 3.

103

104 GGBS was used as a key ingredient because of the proximity of slag works in South Wales
105 (Newport and Port Talbot), with the possibility of creating a market opportunity for local brick
106 manufacturers in the area. GGBS is a by-product obtained in the manufacture of pig iron in the
107 blast furnace and is formed by the combination of iron ore with limestone flux. The presence of
108 GGBS in the current study is to ensure that the final product is durable. The use of a cement
109 replacement material (GGBS) with a lower environmental burden offers opportunities for
110 significant reductions in energy use and carbon dioxide emissions. Additional environmental
111 benefits are the reduction in mineral extraction required for the manufacture of PC.

112

2.4 Lime

Two different types of limes were used in this research – quicklime (calcium oxide) (L1) and hydraulic lime (L2). Both were supplied by Tŷ-Mawr Lime Ltd, Llangasty, Brecon, UK. Some physical properties, oxide and some chemical composition of both limes are shown in Table 3. It may be noted from Table 3 that the composition of L2 is much less than 100%, this is because L2 is a hydraulic lime. Hydraulic limes of far lower quality than quick or slaked lime varieties, the former also comprise of a wide range of compositions of very low proportions. The use of the two different limes provided the research team with a performance profile for the limes. It also allowed the team ample flexibility, especially when making recommendations at the final stage of this work.

2.5 Portland Cement (PC)

A single batch of the cement Portland Cement (PC), manufactured to BS EN 197-1, 2000, and supplied by Lafarge Cement UK, was used throughout this work. Some physical properties, oxide and some chemical composition of the PC can be seen in Table 3. The PC was used for investigating the performance of the PC activated GGBS blended stabilisers, for comparison with the performance of lime activated GGBS blended stabilisers, and as control.

2.6 Sand

Natural sea-dredged sand was used for all the mixes, in accordance with the British Standard requirements for fine aggregate/sand in concrete BS EN 12620:2002+A1:2008. In order to group these various particles into separate ranges of sizes and to determine the relative proportions, by dry mass of each size range, a particle size analysis of the sand was conducted in accordance

with BS EN 933-1 1997. The result of the particle size analysis is shown in Figure 1. The particle size analysis showed that less than 50% of the particles were retained between any two consecutive sieves (5·00 to 0·600mm) and less than 25% in any sieve between 0·300 to 0·150 mm (ASTM C144-04:2008)

3.0 METHODOLOGY

3.1 Mix Composition, sample preparation and testing for the blend used for brick making

The mix designed was adapted from the authors' previous work (Oti et al., 2010, Oti and Kinuthia 2012). The authors have a long experience of soil stabilisation using Lime-GGBS binders and have several publications on the use of this binder (Oti et al., 2009, Oti 2010, Kinuthia and Oti 2012). In this current study, Bottom and Cereal Ash (BA and CA) wastes are the primary target materials mixed at a 1:4 ratio, based on the availability of these waste materials. They were used as full substitutes for primary clay. On the other hand, Magnesium oxide Ash (MA) waste was used as a partial substitute for conventional stabilisers of lime and/or Portland Cement.

Table 4 shows the details of the mix compositions of the laboratory cylinder specimens (50 mm diameter and 100 mm long) made using varying proportions of the mix ingredients at 20% and 10% stabiliser content. The mass density of the mix ingredients for one cylinder sample was 400g. The materials were thoroughly mixed in a variable-speed Kenwood Chef KM250 mixer for 2 minutes before slowly adding the calculated amount of water and mixing for another 2

minutes to achieve a homogeneous mix. Immediately after mixing, the materials were compressed into cylinders. The cylinders were then extruded using a steel plunger (see Figure 2), weighed and wrapped in cling film. The cylinders were placed in sealed plastic containers, and allowed to moist-cure for 7 and 28 days at room temperature of about 20±3°C.

In order to establish the viability of the transition from the laboratory cylinder specimens to actual brick production, a laboratory-scale production of full-size building bricks was carried using the mix composition shown in Tables 4, and using a procedure fully described by Oti et al., 2009.

The unconfined compressive strength testing of the laboratory cylinder specimens was carried out using a Hounsfield testing machine. An average of three specimens per mix composition was tested for unconfined compressive strength, in accordance with BS 1924-2:1990. The mean strength of the three test specimens was determined as the representative strength for a particular mix composition.

Since the major factors influencing the durability of stabilised materials is the degree to which the material becomes saturated with water, the durability assessment of the brick test samples produced with the MA/lime/PC stabilised BA and CA waste in a severe environment was carried out by means of 24 hour repeated freezing/thawing cycles. For the purpose of this study, the freeze-thaw test was performed using the brick specimens made using the BA+CA+PC blend, BA+CA+L1 blend, BA+CA+MA blend, BA+CA+PC+GGBS blend, BA+CA+L1+GGBS blend and the BA+CA+MA+GGBS blend. No freeze-thaw tests were carried out for the laboratory-

scale cylinder test specimens. This is because the brick specimens were more representative of the likely end product of the research work.

For the determination of resistance to freezing and thawing, the bricks test specimens were first dried to a constant weight, at a temperature of 40°C in a Tawnson Mercer desiccator cabinet. A carbon-dioxide absorbing compound (carbosorb) was used for drying. This method of drying was adopted to minimise any sample carbonation that is common in most systems containing hydraulic lime - $Ca(OH_2)$. Drying was accelerated by using silica gel, which was continually replenished on a daily basis. The freezing and thawing test was performed in a Prior Clave LCH/600/25 model $0.7m^3$ volume capacity environmental chamber, in compliance DDCEN/TS 772-22:2006. The experimental cycles were then modified in light of the capabilities of the available equipment to replicate these ideals in DDCEN/TS 772-22:2006. For freeze–thaw, the specimens were maintained at a temperature of – 15 to + 20 °C for 24 hours, as against 8 hours as stipulated in DDCEN/TS 772-22:2006 for the first cycle and 4 hours for subsequent freezing and thawing cycles specified in the British standard. The test methodology used in this study was therefore viewed as a more severe test method. The 24-hour cycle was repeated 100 times, and the weight losses at 7, 28, 50, 75 and 100 cycles recorded. At the end of the 100th freeze/thaw cycle, visible damage on the exposed faces of the stabilised bricks was recorded.

200 **3.2 Mix Composition, sample preparation and testing for the sustainable mortar**

201

202 Six mortar mixes were prepared as part of the initial preliminary trial at 0.5 water binder ratio.
203 The binder:sand ratios were adopted from the mixes used on various occasions in previous
204 studies by the authors in an investigation on the strength and workability of sustainable masonry
205 mortars using PC and Lime activated GGBS systems (Oti et al., 2010). Under this current
206 research work, PC, quicklime and hydraulic lime were each separately used as stabilisers to
207 combine with the Cereal Ash (CA) waste at stabilsier:CA ratios of 30: 70 and 50: 50 as detailed
208 in Table 4.

209

210 For the fresh mortar preparation, the mix ingredients were pre-mixed in the dry state in a variable
211 speed Kenwood Chef Major KM250 mixer for 1 min, to ensure a homogeneous mixture, before
212 incrementally adding small amounts of water until the desired consistence were attained at about
213 3 min. For compressive strength testing, 50 mm × 50 mm cube specimens were prepared for all
214 mixes at 0.5 w/b ratio. The cubes were filled with fresh mortar in three layers on a vibrating
215 table to ensure adequate compaction of the mortar. The cube specimens were covered with
216 waterproof film to prevent moisture loss, and stored under controlled conditions of about 20
217 [± 2]°C. After 24 h, the specimens were de-moulded, weighed, labelled and moist cured until the
218 time of testing (7 and 28 days). The compressive strength testing for all the moist cured cubes
219 specimens was carried out in a manner similar to that for CEN standard sand in BS EN 413-
220 2:2005 and BS EN 196-1: 2005 using a Hounsfield testing machine capable of loading up to

10 kN; the axial load was applied at a compression rate of 2 mm/min, with an average of six cubes per test, taken as the representative compressive strength values.

4.0 RESULTS

4.1 The unconfined compressive strength of the cylinder test specimens

Figures 3 and 4 illustrates the 7 and 28-day unconfined compressive strength development of the cylinder specimens made using Bottom and Cereal Ash (BA and CA) waste upon stabilisation with MA/lime/PC-based unblended stabiliser and then each stabiliser blended with GGBS. The stabiliser content is 10 and 20% respectively, by mass of the waste ashes.

In general, the compressive strength increases with the increase in age. There is significant strength gain with age up to 28 day for the mixtures stabilised with lime and GGBS (BA+CA+L1+GGBS). The gain in unconfined compressive strength with age was lower for the mixture with PC and GGBS (BA+CA+PC+GGBS) at all stabiliser content (10% and 20%). The lime activated GGBS stabiliser has significantly higher influence in strength than the equivalent PC-based system as observed from the results. It was observed from the compressive strength results that the strength of all the stabilised cylinder specimens tended to decrease with the decrease in stabiliser content.

4.2 The unconfined compressive strength cube test specimens

Figure 5 shows the compression test results of the cube test specimens for use in the production of sustainable masonry mortar for brick joint and plaster. The specimens were tested at 7 and 28 days. The highest compressive strength at any age was produced by the cube test specimen made from 50% cereal ash waste and 50% Portland cement (50% PC replacement level). In all mixes, there was a progressive reduction in compressive strength value as the PC, quicklime and hydraulic lime replacement level in the cube test specimen increased from 50 to 70%. In general, the compressive strength increases with the increase in age. The gain in unconfined compressive strength with age was lowest for the mixtures with quicklime and cereal ash waste.

4.3 The effect of freezing and thawing on stabilised brick specimens

Figure 6 illustrates the record of the percentage weight loss of the stabilised brick test specimens made using the BA+CA+PC blend, BA+CA+L1 blend, BA+CA+MA blend, BA+CA+PC+GGBS blend, BA+CA+L1+GGBS blend and the BA+CA+MA+GGBS blend, for up to the 100^{th} freezing and thawing cycles. The weight losses for all stabilised brick test specimens were within the range of 1.2-1.60% at the end of the 7^{th} cycle. A steep increase in weight loss of about 1.4-1.9% was observed at the end of the 28th cycle, for all stabilised brick test specimens. No further significant increases in weight loss were observed at the end of the

265 100^{th} cycle for all the stabilised bricks. Overall, the highest weight loss at the end of the 100^{th}
266 freezing and thawing cycle was less than 2%, which is considered good performance for
267 stabilised brick test specimens subjected to 24-hour repeated freezing and thawing cycles. The
268 analysis of results of the examination of the specimens after the 100^{th} freezing and thawing
269 showed no damage of any type. Table 5 further presents the detailed assessment of the results the
270 stabilised brick test specimens, after the 100^{th} freezing and thawing cycle.

271

272 **5.0 DISCUSSION**

273

274 There were variations in unconfined compressive strength for the stabilised cylinder specimens
275 made using Bottom Ash (BA) and Cereal Ash (CA) wastes upon stabilisation with unblended
276 MA/lime/PC-based stabiliser (BA+CA+PC, BA+CA+L1 and BA+CA+MA) at 10 and 20%
277 stabiliser contents. On the other, similar trends were observed when the BA and CA wastes were
278 stabilised with GGBS blended with MA/lime/PC-based stabiliser (BA+CA+PC+GGBS,
279 BA+CA+L1+GGBS and BA+CA+MA+GGBS). For the entire system investigated, the
280 unconfined compressive strength at the time of testing increases with the curing age of the
281 specimen. The compressive strength values obtained using the blended stabilisers are better,
282 relative to those observed for the unblended stabilisers. The strength values also increased as the
283 stabiliser content in the mix increases from 10 and 20%. The reasons for the improved
284 performance may include better material size distribution and variable mineral composition.

285

286 The explanation for the variations in the strength of the various stabilised cylinder test specimens
287 is due to complexity of the various pozzolanic and other reactions involved in the hydration
288 processes within the systems. The different stabiliser blends contain varying amounts of residual
289 lime, resulting in differences in the pH of the systems and hence differences in reacting ion
290 species. This may be one of the many factors involved to produce strength variations in the
291 different systems. By blending CaO with GGBS, the combined pozzolanic reactions involved
292 result in more gel formation and hence pore refinement and preventing the formation of more
293 voids, with resultant hardened paste. GGBS may also play the role of diluting the stabilised
294 system. This would enable efficient CaO hydration. In addition to the above hypotheses, GGBS
295 also acts by providing a surface upon which lime can be adsorbed and subsequently interact by
296 activating the hydration process with the enhanced pH environment. Higher pH is beneficial for
297 the hydration and hence strengthening process. It is hypothesised that the sustained pH may be a
298 contributing factor to the higher strength values observed in the BA+CA+L1+GGBS system
299 relative to the BA+CA+PC+GGBS system. In the PC system where lime is readily consumed as soon
300 as it is produced, in the activation of GGBS, the pH of the system is likely to be lower compared to that
301 prevailing in a system higher in lime when quicklime is directly used. The continued formation of C–
302 S–H gel within the pore structure has pore-blocking effect, providing strength in the process
303 (Wild et al., 1997, 1998; Zhang, 1995, Antiohos et al., 2008).

304 There were variations in unconfined compressive strength for the blended mortar specimens
305 made using PC-Cereal Ash (CA) waste, quicklime (L1) – CA waste and hydraulic lime (L2) –
306 CA waste blends at 30: 70 and 50: 50 replacement ratios. For the whole system, the unconfined
307 compressive strength at the time of testing appears to increase as the age of the specimen
308 increases. The compressive strength values obtained using the 50: 50 replacement ratios blended

mortars are better, relative to those observed for the 30: 70 (PC/L1/L2:CA) replacement ratios. This trend was however expected. The reasons for the improved performance at higher stabiliser content (50% PC/L1/L2) may include better material size distribution, variable mineral composition and higher binder content.

The higher strength observed for the blended mortar specimens made using 50%PC-50% CA waste at all curing ages is attributed to the substantial calcium silicate hydrate (C–S–H) gel formation as reported in previous research studies (Escalante–Garcia and Sharp, 2004; Ganesh Buba and Sree Rama Kumar, 2000). Evidence from previous work where PC was partially replaced with pozzolanic materials such as condensed silica fume, fly ash and ground clay bricks has been reported to be beneficial in substantial pore structure refinement, reduction of ionic mobility, Calcium Hydrate (CH) consumption and the reduction of permeability of binder matrix with curing age (Khatib and Wild 1998, Kinuthia et al., 1999; O'Farrell 1999, Santhanum et al., 2002). Replacement of traditional stabilisers such as lime and/or Portland cement to mitigate the environmental effects associated with the manufacture of the traditional stabilisers (carbon dioxide emission, depletion of natural raw materials amongst others) in mortar and concrete have been on-going.

The properties of the hydrated product that make up the mortars are also governed by properties of the C–S–H gel, such as its amount, porosity, permeability, and fineness of all reactants involved, efficiency of mixing, temperature and curing time. When CA waste is blended with PC in the presence of water, the hydration of phases present in PC (mainly C_3S, C_2S, C_3A and C_4AF) results in cementitious products (C-A-H, $\overline{CA}-\overline{SH}$, C–S–H gels among other complex

compounds) are formed, similar to those occurring when CA waste is blended with lime (L1 or L2) in the presence of water. As the level of PC or Lime is increased from 30-50%, the strength property of the mortar improved, this is attributed to more cement hydration and lime-induced pozzolanic hydration respectively (Boardman et al., 2004, Kinuthia et al., 1999). The differences in strength property of PC and Lime blended mortar can be attributed to differences in the hydration reactions between lime and PC. In the absence of GGBS, the hydraulic activities in the PC-CA mortar mixtures are likely to result in better C-S-H formation as PC is capable of self-hydration as well as result in pozzolanic hydration from the lime by-product of PC hydration. In contrast, the Lime-CA mortars would only rely on pozzolanic hydration from the lime.

As was the case of variations in the stabilised product unconfined compressive strength, there were variations in the weight loss due to repeated freezing and thawing behaviour for the stabilised brick test specimens. For all the systems, the weight loss due to repeated freezing and thawing appeared to decrease as the number of cycles increased. The assessment conducted showed no damage of any type for all stabilised systems

During the freezing and thawing cycles, the results in the current study shows that stabilised brick test specimens were able to resist the ice crystallization pressure, resulting only in minor losses in weight without breaking. The majority of researchers dealing with stabilised building materials development (Edwards, 1991, Kværnø and Øygarden, 2006 and Cultrone et al., 2007) agree that in most cases freezing of pore water inside a masonry building material occurs when the material is subjected to repeated freezing and thawing. The expansion of water on freezing causes a reduction of granular interlock within the stabilised material. The ensuing migration of

unfrozen water towards the freezing front creates further disturbance to material moisture properties and texture. The presence of pockets of unstabilised material, due to poor material mixing, may also contribute to deterioration of the stabilised product. However, throughout the freezing and thawing cycles in the current work, close extermination shows no noticeable evidence of cracks in the unfired clay bricks. The results suggest that the stabilised brick test specimens in this study were well mixed, developed good strength and may be considered suitable for use in a severe environment.

In the neighbourhood of most biomass plants worldwide, huge piles of CA and BA wastes are in abundance. In most cases, these stockpiles of waste may increase fragility of ecosystems, thus, stretching the landscape beyond it ultimate limits of natural ecological equilibrium and potentially threatening an environmental crisis (Roa, 2007). Because of the scarcity of land and the high costs of management and treatment associated with disposal of MA, CA and BA wastes, this research has been devoted to finding beneficial uses for the waste streams. On-going laboratory-based fine-tuning operations will simulate sustainable bricks and mortar incorporating waste with a range of possibilities such as reducing the stabiliser content by 80%. Environmental impact analyses relating to the formulated products, together with the product life cycle, will also be reported in sequel publications. Work on the microstructural analyses of the stabilised product will be established using scanning electron microscopy (SEM) and thermo-gravimetric analysis (TGA), among other analytical tools. At this stage, it is therefore not possible to devolve the reaction mechanisms involving all the different phases of biomass waste and conventional stabilisers. The main focus at present has been on engineering performance.

6.0 CONCLUSIONS

The results obtained suggest that there is potential for the use of cereal ash, bottom ash and Magnesium oxide waste streams for the manufacture of stabilised masonry bricks and sustainable masonry mortar for brick joints and plaster among other applications. This will facilitate more sustainable construction. The following conclusions are drawn from this research:

1. The preliminary cylinder test specimens made using bottom ash and cereal ash wastes, stabilised with lime-GGBS blended stabiliser showed highest overall potential for brick manufacture. The strength characteristics were improved by the presence of both lime and GGBS whose combined action formed a strong bound. The lime and GGBS offers other benefits in enhancing all-round performance, including volume stability and overall durability.
2. The preliminary mortar specimens made using Portland cement and cereal ash blend at 50% cement replacement level showed highest overall potential for mortar manufacture. The strength characteristics of the mortar systems appear to increase as the age of the specimen increases.
3. The stabilised brick test specimens were able to withstand 100 cycles of repeated 24 hour repeated freezing and thawing cycles. The freeze/thaw test was a feasible means of durability assessment of the stabilised product.

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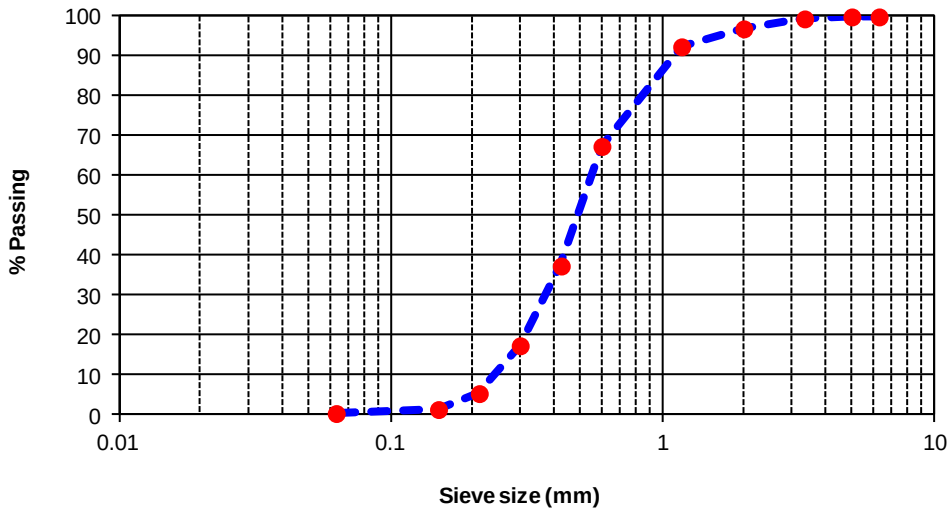

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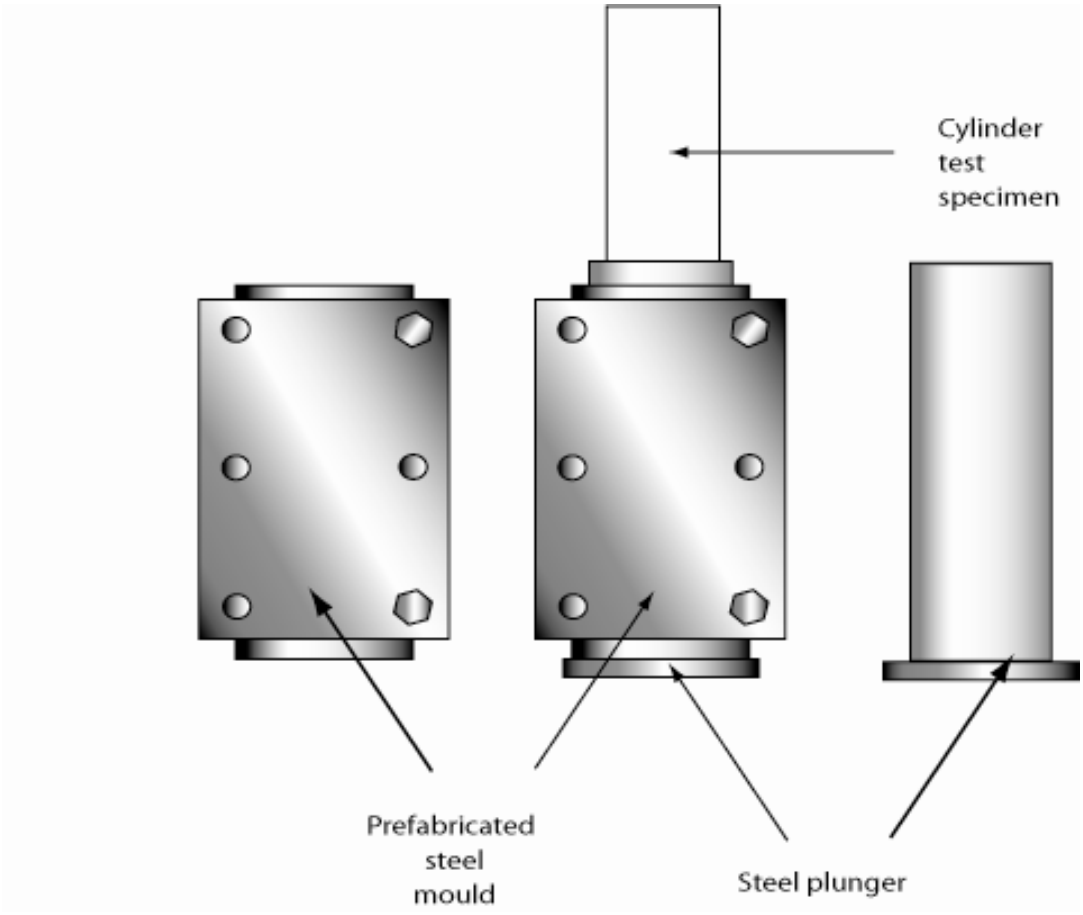
495 **Figure 1** -The particle size analysis of sand



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497 **Figure 2 -** Steel mould and the extruded cylinder test specimen (extension collar not shown)

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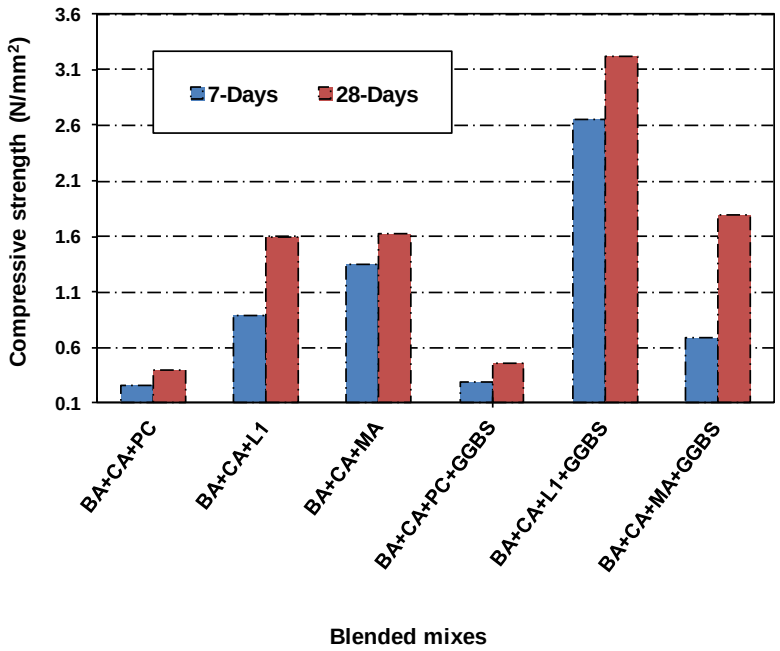

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501 **Figure 3 -** The compressive strength of the stabilised system up 28-day moist curing age at 20% stabiliser content.

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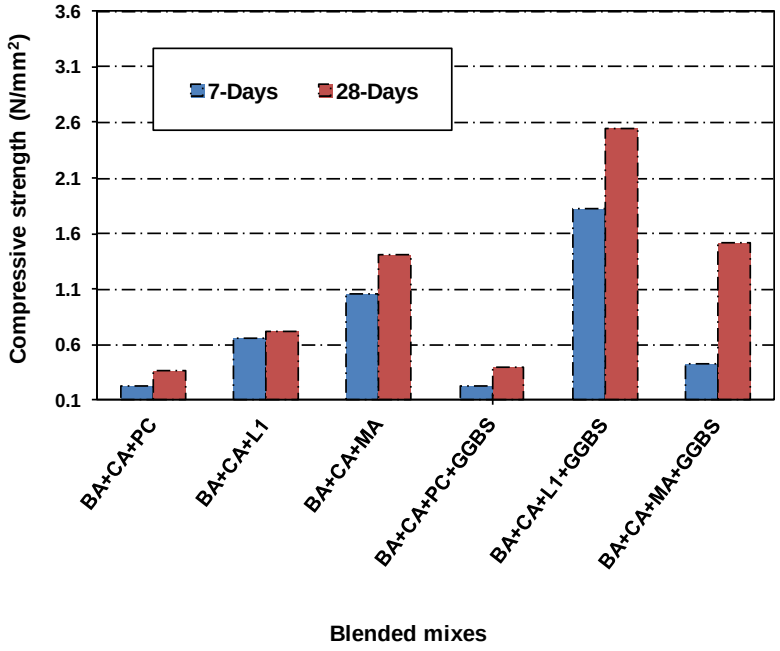

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504 **Figure 4 -** The compressive strength of the stabilised system up 28-day moist curing age at 10% stabiliser content

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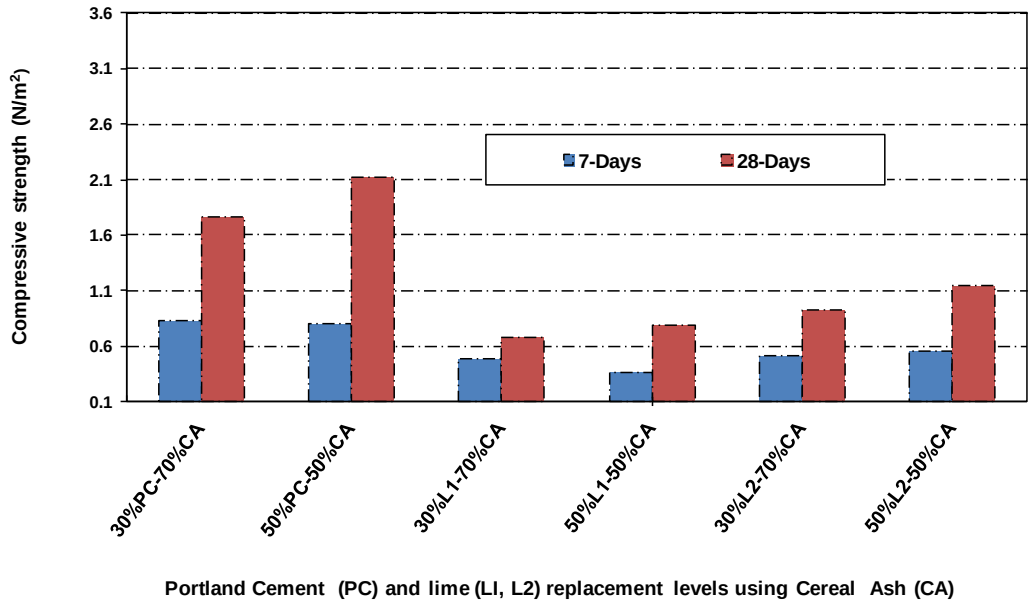

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507 **Figure 5-** The compressive strength of the blended mortar system up 28-day moist curing age

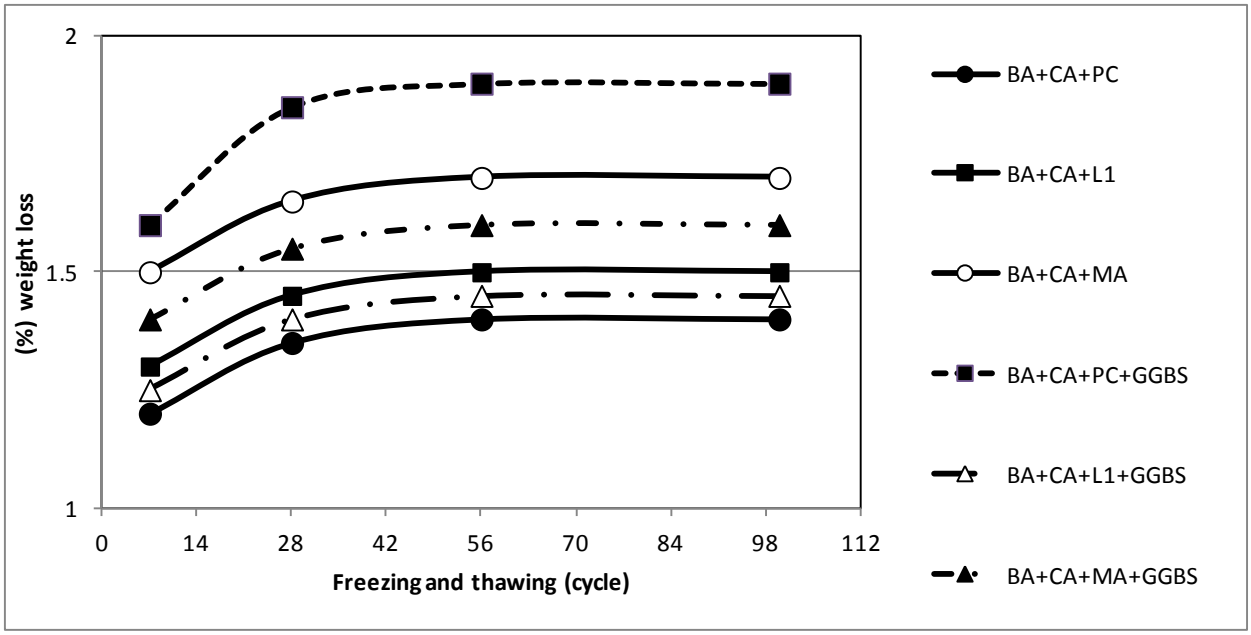

Figure 6 - The percentage weight loss on all unfired clay bricks during freezing and thawing cycles

523 **Table 1** - Some physical properties and chemical compositions of CA and BA

Element	CA (%)	BA (%)
SiO_2	88.04	59.20
Al_2O_3	3.16	22.42
Fe_2O_3	0.56	8.32
CaO	1.04	1.34
MgO	0.62	1,53
Na_2O	3.16	0.23
K_2O	0.00	1.2
TiO_2	0.20	0.00
LOI	3.22	5.76
Some Pysical properties		
pH	9.8	12.6
Moisture (%)	0.3	24.6
Total Phosphorus µg/g	–	3770
Organic matter (%)	–	36.3
Notation		
CA = Cereal Ash Waste		
BA = Bottom Ash Wastes		

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525 **Table 2** -The oxide compositions and sieve analysis of MgO Ash waste

Oxides	Composition (%)
CaO	8.5
MgO	72
SiO_2	3.5
Fe_2O_3	3
Others	13
Sieve (mm)	**% passing**
2.00	100
0.50	100
0.25	90
0.063	70

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527 **Table 3** - Some physical properties, oxide and chemical compositions of GGBS, Lime and PC

Oxide	L1 (%)	L2 (%)	PC (%)	GGBS (%)
CaO	89.2	66.6	63.00	41.99
SiO_2	3.25	4.77	20.00	35.35
Al_2O_3	0.19	1.49	6.00	11.59
MgO	0.45	0.56	4.21	8.04
Fe_2O_3	0.16	0.71	3.00	0.35
MnO	0.05	0.08	0.03 - 1.11	0.45
S^{2-}	< 0.01	< 0.01	–	1.18
SO_3	2.05	< 0.01	2.30	0.23
SO_4	2.46	< 0.01	–	–
K_2O	0.01	0.25	–	–
N_2O	0.02	0.04	–	–
CO_3	4.00	3	–	–
Soluble Silica	1.10	4.77	–	–
Free Lime	51.10	39.4	–	–
Properties				
Insoluble Residue	4.1	2	0.5	0.3
Bulk Density (kg/m³)	(1150-1300)	490	1400	1200
Relative Density	2.8	2.4	3.1	2.9
Blaine fineness (m^2/kg)	430-1450	300-1400	365	450
pH	13.9	12.9		
Colour	Off - White	White	Grey	Off - White
Glass Content	–	–	–	≈ 90

Notation
L1 = Quicklime
L2 = Hydraulic lime
PC = Portland Cement
GGBS = Ground Granulated Blastfurnace Slag

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Table 4 - Mix composition for one cylinder and mortar samples

Mixes	Weight of mix ingredients (g)									Test	
	BA	CA	PC	L1	L2	MgO	GGBS	Water	Sand	Strength	Freeze- thaw
At 10% Stabiliser Content											
BA+CA+PC	252.96	63.24	31.62	0.00	0.00	0.00	0.00	52.17	0.00	✓	✓
BA+CA+L1	252.96	63.24	0.00	31.62	0.00	0.00	0.00	52.17	0.00	✓	✓
BA+CA+MA	252.96	63.24	0.00	0.00	0.00	31.62	0.00	52.17	0.00	✓	✓
BA+CA+PC+GGBS	252.96	63.24	9.49	0.00	0.00	0.00	22.13	52.17	0.00	✓	✓
BA+CA+L1+GGBS	252.96	63.24	0.00	9.49	0.00	0.00	22.13	52.17	0.00	✓	✓
BA+CA+MA+GGBS	252.96	63.24	9.49	0.00	0.00	0.00	22.13	52.17	0.00	✓	✓
At 20% Stabiliser Content											
BA+CA+PC	231.88	57.97	57.97	0.00	0.00	0.00	0.00	52.17	0.00	✓	×
BA+CA+L1	231.88	57.97	0.00	57.97	0.00	0.00	0.00	52.17	0.00	✓	×
BA+CA+MA	231.88	57.97	0.00	0.00	0.00	57.97	0.00	52.17	0.00	✓	×
BA+CA+PC+GGBS	231.88	57.97	17.39	0.00	0.00	0.00	40.58	52.17	0.00	✓	×
BA+CA+L1+GGBS	231.88	57.97	0.00	17.39	0.00	0.00	40.58	52.17	0.00	✓	×
BA+CA+MA+GGBS	231.88	57.97	0.00	0.00	0.00	17.39	40.58	52.17	0.00	✓	×
Mortar Mix composition											
30%PC-70%CA	0.00	283.5	121.5	0.00	0.00	0.00	0.00	203	1213	✓	×
50%PC-50%CA	0.00	202.5	202.5	0.00	0.00	0.00	0.00	203	1213	✓	×
30%L1-70%CA	0.00	283.5	0.00	121.5	0.00	0.00	0.00	203	1213	✓	×
50%L1-50%CA	0.00	202.5	0.00	202.5	0.00	0.00	0.00	203	1213	✓	×
30%L2-70%CA	0.00	283.5	0.00	0.00	121.5	0.00	0.00	203	1213	✓	×
50%L2-50%CA	0.00	202.5	0.00	0.00	202.5	0.00	0.00	203	1213	✓	×

Notes
Stabiliser content =20%, The ratio of PC/L1/MgO:GGBS=3:7, BA; CA= 4:1, BA= Bottom Ash waste, CA = Cereal Ash waste, MA=Magnesium Oxide Ash waste, PC= Portland Cement, GGBS= Ground Granulated blast-furnace slag, L1=Quicklime, L2= Hydraulic lime, For all the mortar mixes, the the water:binder ratio=0.5

546 **Table 5** - Assessment of damage on the unfired clay bricks at the end of the freezing/thawing cycles (DDCEN/TS
547 772-22:2006)

Description of damage	Remarks
Crater	No craters were observed at the end of the 100th freezing /thawing cycle for all the stabilised bricks under investigation.
Hair Crack > 0.2 mm	No hair cracks were observed for all the specimens during the entire freezing and thawing cycle.
Minor crack	At the end of the 100th freezing and thawing cycle, no minor cracks were observed.
Surface crack > 0.2 mm	From the begining to the end of the freezing and thawing cycles, no surface cracks were observed in all the brick types.
Chipping, peeling, scaling	No type of chipping, peeling, scaling were noted at the end of the 100th freezing and thawing cycle.
Fracture	At the end of the 100 freezing and thawing cycle, no fracture was observed.
Spalling, delamination	No spalling or delamination were noted during the entire freezing and thawing cycle.

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